A coupled atmosphere-wildland fire meso-scale model

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1. Introduction

A tight interaction exists between the development of a wildfire and the local meteorology near the front. The extreme convective effects of the heat released by the fire can modify the local wind circulation and consequently modify the fire propagation. Numerical coupling of a fire spread model with an atmospheric model has already been the subject of numerous study, most notably the work by Clark et al (2004).

In this study we use the Meso-NH meso-scale numerical model in a Large Eddy Simulation (LES) configuration coupled to a simplified physical front tracking wildfire model to investigate the differences induced by the atmospheric feedback in propagation speed and behaviour. Simulations of typical experimental configurations show a good response of the coupled fire-atmospheric model. Numerical results matches qualitatively observed values for fire induced winds and convection. Both numerical models already have operational usage and might ultimately be run to support decisions in wildfire management

2. WildFire simulation

Our approach for the simulation of spatial phenomenon combines discrete event simulation (Zeigler 2000) and front tracking (Glimm et al.1996).

Front tracking methods are used to study interface or boundary dynamics. In this front tracking application, phenomenon behaviour is represented by a polygon, which is the discrete view of the continuous front system.

In figure 1 the polygon is decomposed into front markers that represent points of the interface. To move in space and time, each marker has a displacement vector and a reference position.

The interface evolves in a domain, that contains different area (vegetation type, roads, fire breaks…) also defined by polygons. The simulated interface evolves every time an agent has to move by a quantum distance, generating an event.

A collision event, is schedueled with a "time to advance", that is computed explicitly using the displacement vector.

In the forest fire model, the displacement vector is computed at every collision to be normal to the front. The speed of each marker is computed by the rate of spread model using the local wind, local slope in the marker direction and local vegetation at the location of the marker. Using this schema ensures that there is no « ghosting » effect and no global time stepping constraints.

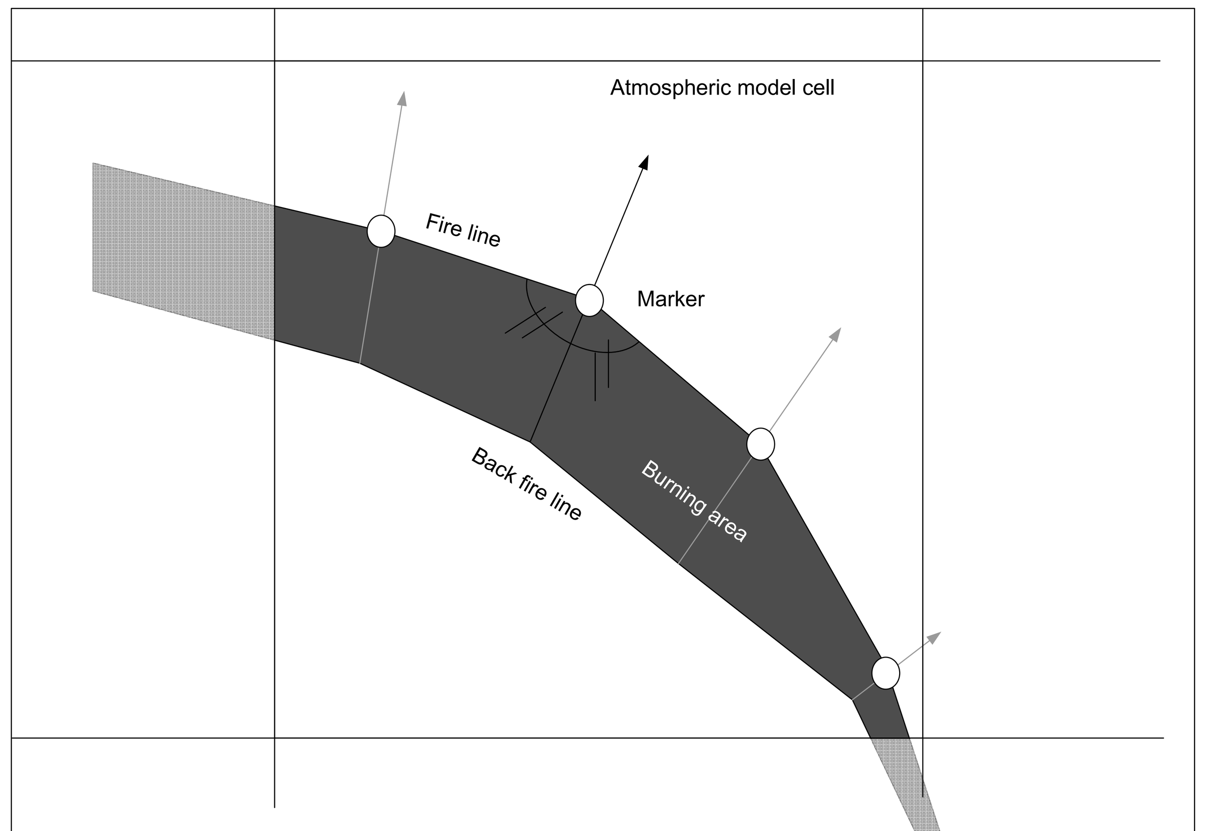


Figure 1) Front tracking fire simulation

3. Fire spread model

This physical based model has been developped to provide an analytical formulation of the propagation speed given a slope angle, wind speed, and fuel parameters. It is based on the hypothesis that the heat transfer is due to the radiation, of the front fire, assimilated to its tangent plane (figure 2).

$$r = 1 + A\frac{r(1+\sin\gamma - \cos\gamma)}{1+\frac{r}{r_0}\cos\gamma}$$

$$\tan\gamma = \tan\alpha + \frac{U}{u_0}$$

With

$r = \frac{R}{R_0}$ Reduced rate of spread

R Rate of spread in $m.s^{-1}$

R_0 Rate of spread without wind and slope in $m.s^{-1}$

γ Tilt angle

U Normal wind velocity in $m.s^{-1}$

α Local slope angle

u_0 Vertical velocity in the flame without wind and slope in $m.s^{-1}$

A ratio of radiated energy over ignition energy

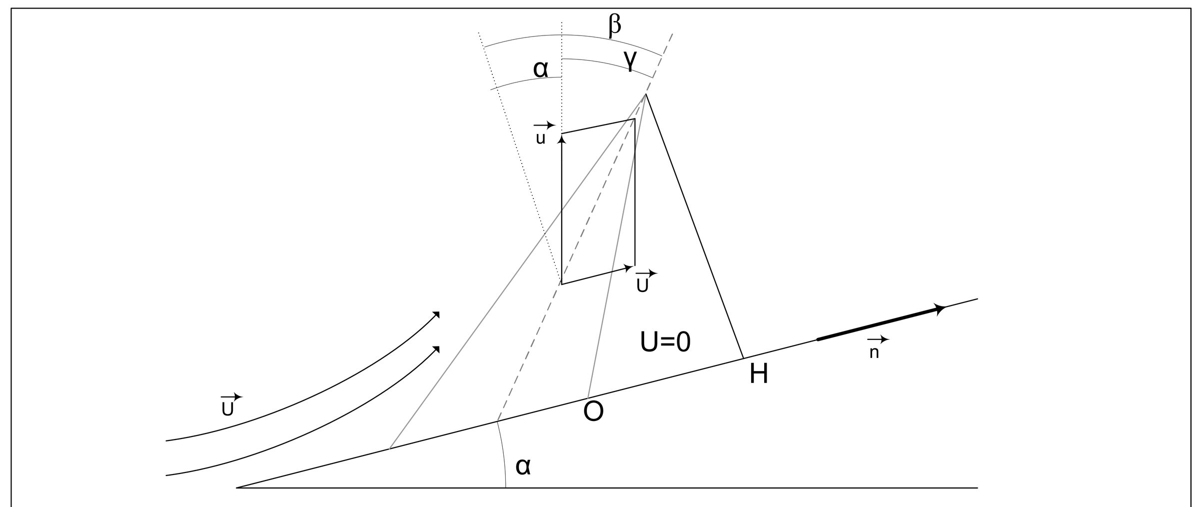


Figure 2) Fire rate of spread model

4. Atmospheric coupling

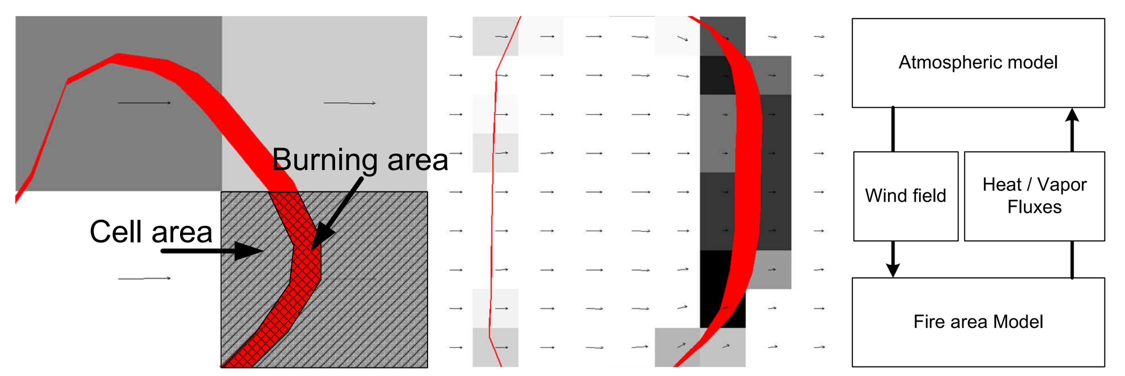
The atmospheric model, Méso-NH is the non-hydrostatic mesoscale atmospheric model of the French research community. It has been jointly developed by the Laboratoire d'Aérologie (UMR 5560 UPS/ CNRS) and by CNRM-GAME (URA 1357 CNRS/Météo-France). The model is intended to be applicable to all scales ranging from large (synoptic) scales to small (large eddy) scales and it is coupled with an on-line atmospheric chemistry module.

The forest fire is running as a sub-mesh model in Meso-NH. The coupling is done at each atmospheric time-step. Coupling between the fire spread and atmospheric model is done through wind fields of the first atmospheric level.

Coupling beween the atmosphe and the fire model is done though total heat and water vapor flux.

The burning raster is generated at every step using the method shown in figure 3.

This raster is then multiplied by the nominal heat and water vapor flux to generate the MesoNH inputs.



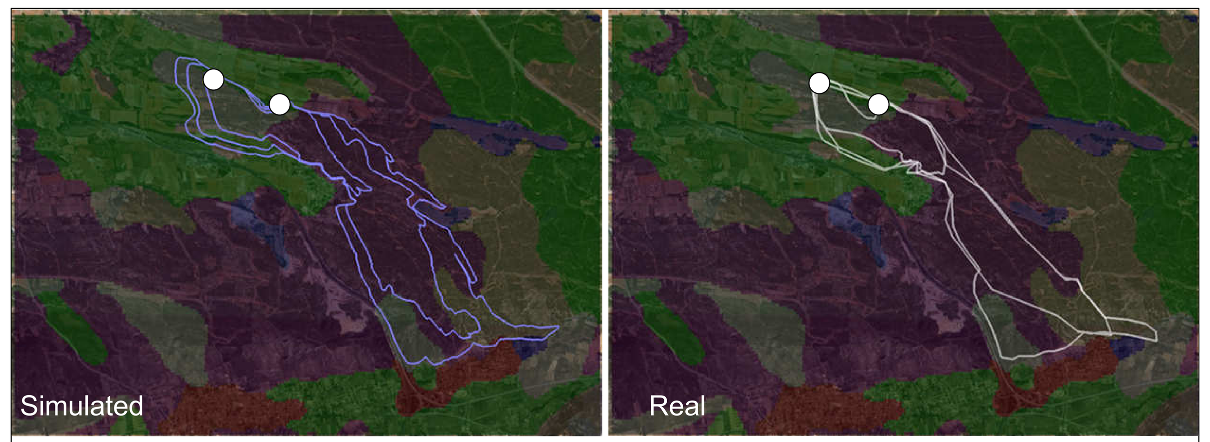
Integration of burning area is made on every MesoNH grid cell (shades of gray corresponds to ratio burning area / cell area).
The red shape is the actual fire front.

Figure 2) Fire model integration on MesoNH mesh

5. Results

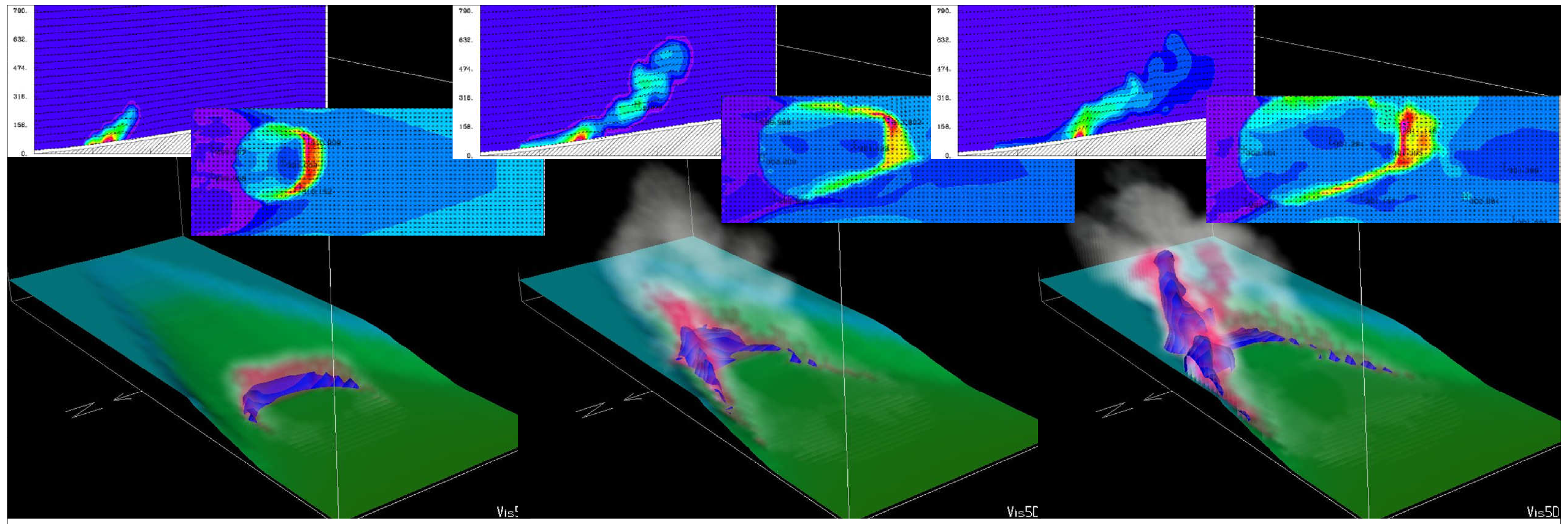
The fire spread model has already been validated using the Lançons benchmark, a well documented real fire that occured in 2001 (figure 4). Figure 5 shows a 3d view of TKE for a fire propagation over a canyon, fire accelerates the local wind forced in the athmospheric model providing the coupling loop.

Figure 6 presents an horizontal and a vertical cross section for two idealized cases. Strong differences exist between coupled and non coupled fire shapes, furthermore, the cross section from a large fire line case shows the creation of a fire plume with a velocity profile and altitude comparable to experimental data from Adams et al. (1972).



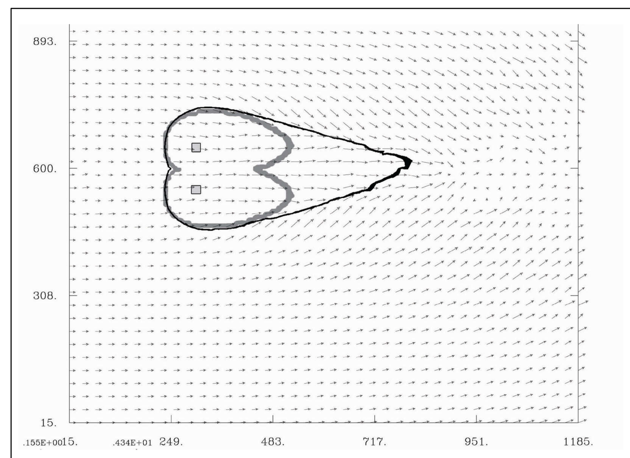
Dots represent ignition points (9h40). Contours are fire front at 12h, 14h30 and 16h30. Colors represents vegetation, simulation time is 2 minutes.

Figure 4 : Simulation results, Lançons

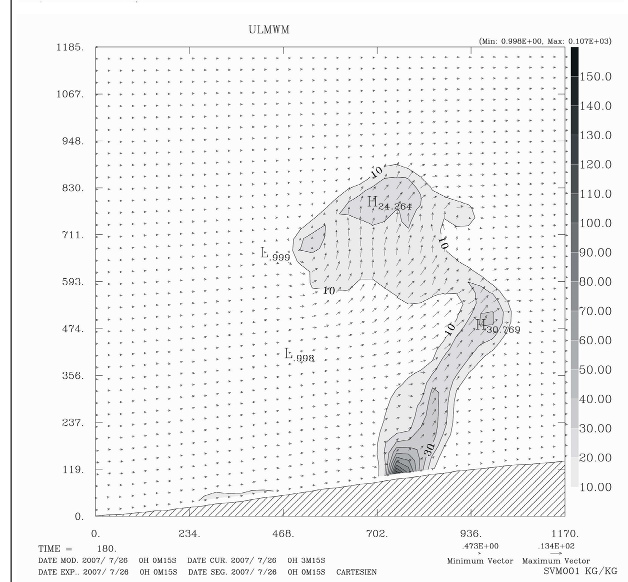


Simulation of a fire propagation over a canyon. Grid count is 80*30*40 points with mesh size of 40*40*40 meters. Simulation wall time is 40 minutes on 4 CPU 3Ghz Intel Xeon processors. Simulation duration is 16 minutes with a time step of 1 second. The 3D view is TKE with the solid part being an iso surface of 1.5 m²/s², the transparent part of the volume is TKE ranging from 1.5 m²/s² to 0. 2D views are the vertical cross section showing wind vectors over TKE and horizontal cross section showing wind over temperature for the first atmospheric layer. Wind vectors range from 2 to 8 $m.s^{-1}$, temperature from 290 (blue) to 340 (red).

Figure 5 : Simulation result 3D canyon



Simulation of a two point ignition without slope after 600 seconds. Fire lines are shown for the coupled (black) and non-coupled (grey) propagation. Arrows denote the horizontal 10 meters wind vectors of the coupled case. The thin dark point represents the initial ignition point for both cases. Strong interaction with the wind created a peak in the front that cannot be simulated without coupling.



Vertical cross section at Y=600m of simulation of an large line ignition with slope after 180 seconds.
Shading represents concentration of the injected passive tracer and arrows wind vectors
In this case the head fire rate of spread increased from 0.2 (without coupling) to 0.5 m.s-1 (with coupling). maximum wind velocity of 24 m.s-1 in the plume. Significant concentration of tracer is here reaching an altitude of 850 meters.

Figure 6 : Simulation result, idealized cases

6. Conclusion

By using simple coupling methods, the atmospheric model is able to respond meaningfully to the injected heat and vapour fluxed. The fire spread and regime are also strongly influenced by the feedback from the atmosphere, with winds accelerating about an order of magnitude faster than the ambient wind near the front.

In terms of rate of spread, the coupled model shows that in case of slope, strong acceleration can occur before a steady rate can been reached. Moreover, simulated fronts show local deformations that are typical of a real wildfire front. Both these local acceleration phases and deformations exist in the reality and may be impossible to simulate using conventional fire spread model.

Overall, the main aim of this work was to demonstrate the feasibility of atmospheric-fire coupling with Meso-NH. Qualitatively, the result provides a good numerical match with simple fire driven atmospheric phenomena.

Quantitative studies need now to be performed to validate the correctness of the coupling. This quantitative study has to be performed along with experiments that will track the fire as the atmosphere during a real wild fire.

Furthermore, other variables, such as water vapour, CO², as well as a more precise schema for the burning phase has to be integrated to enhance the quality of the coupling.

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EGU 2009, Vienna, - Fire in the Earth System-
This research is supported by the CNRS under the PEPS program number 07_36